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LARGE-AREA SHEET TASK
ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

C. S. Duncan, R. G. Seidensticker, and
J. P. McHugh

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1. SUMMARY

The thermal stress models were used to test the effect of melt level on stress generation and growth velocity. The results indicate that melt level has only small effects on stresses but significant effects on growth velocity. These results are consistent with experimental growth from measured melt levels. A new low-stress design concept is being evaluated with the models. A width-limiting version of the low-stress J460 configuration was tested experimentally with results consistent with the design goals.

2. INTRODUCTION

Silicon dendritic web is a single-crystal silicon ribbon material which provides substantial advantages for the low-cost manufacture of solar cells. Growth from a melt of silicon without the use of constraining dies is a significant feature of the process which results in an oriented single-crystal ribbon having excellent surface characteristics. In common with other more typical processes such as Czochralski growth, impurity rejection into the melt permits the use of less pure "solar grade" starting material without significantly affecting cell performance. A unique property of the dendritic web process is the growth of long ribbons of controllable width and thickness which not only facilitates automation of subsequent processing into solar cells, but also results in high material utilization since cutting and polishing are not required.

On the present contract, three broad areas of work are emphasized:

1. The development of thermal stress models in order to understand the detailed parameters which generate buckling stresses, and the application of these models to the development of new low-stress design concepts.

2. Experiments to increase our understanding of the effects of various parameters on the web growth process and to complement and verify the results of the modeling effort.

3. The construction and utilization of an experimental web growth machine which contains in a single unit all the mechanical and

electronic features developed previously so that experiments can
be carried out under tightly controlled conditions.

The principal objective of this work has therefore been to
expand our knowledge and understanding of both the theoretical and
experimental aspects of the web growth process to provide a solid base
for substantial improvements in both area throughput and web crystal
quality, and to develop the tools necessary to carry cut this objective.

During this reporting period, the model was used to test the
effects of melt level on growth behavior and to generate a new low-
stress growth concept. A width-limiting version of the low-stress J460
design was tested experimentally.

3. TECHNICAL PROGRESS

3.1 Thermal Modeling

For our present purposes, developmental work on the model has essentially been completed, and the modeling effort during the present report period has been mainly the application of the models to specific questions. Specifically, the models were directed toward the effects of melt height on web growth and to the continued development of concepts for very small buckling stress growth systems.

It has long been known that changes in melt height have significant effects on web growth, especially in the velocity required to maintain a constant thickness of the ribbon. Early work with modeling[1] suggested that melt height changes could also influence the residual stresses in the material, and some experimental data tended to confirm this observation. Recently, however, more sophisticated growth systems have been developed within which the melt level effects on stress are not quite as obvious, although the influence on growth velocity at constant thickness is still significant. Following this current experimental lead, some modeling work was done to investigate the effect of melt level within current growth configurations such as the J460.[2] This type of parametric analysis also seemed appropriate as an introduction to anticipated future work with dynamic thermal trimming.

Chosen for study was the standard J460 growth configuration, shown schematically with the resulting (▵T)" curve in Figure 1 (taken from Ref. 2); the concomitant delta x-stress curve is shown in Figure 2. Both curves represent a melt level such that the growth front is even with the bottom of the susceptor lid (LIN = 0). Additional modeling runs were then made for this configuration with the interface 1 and 2 mm (LIN = 0.1 0.2 cm) below the bottom of the lid. It was found

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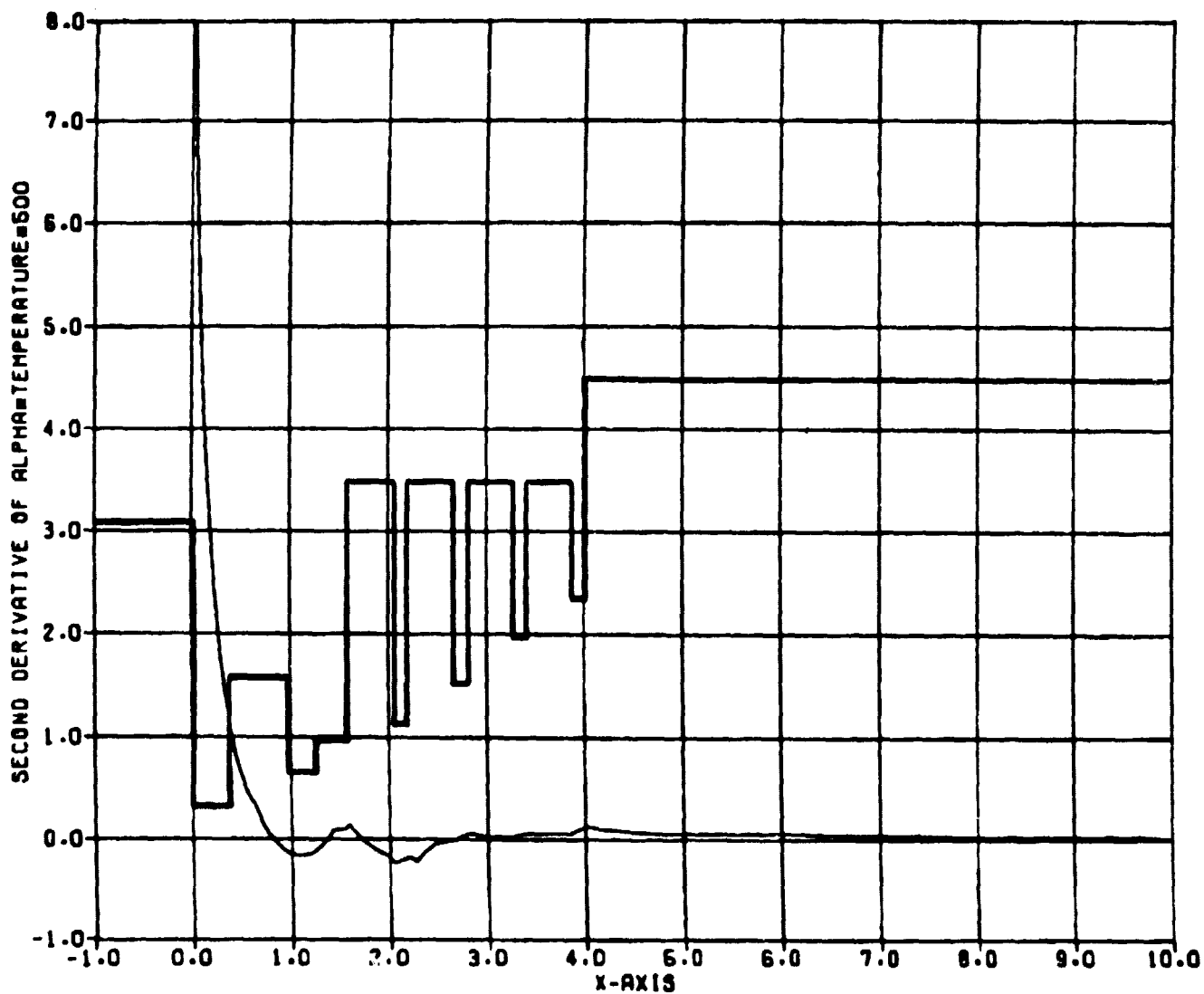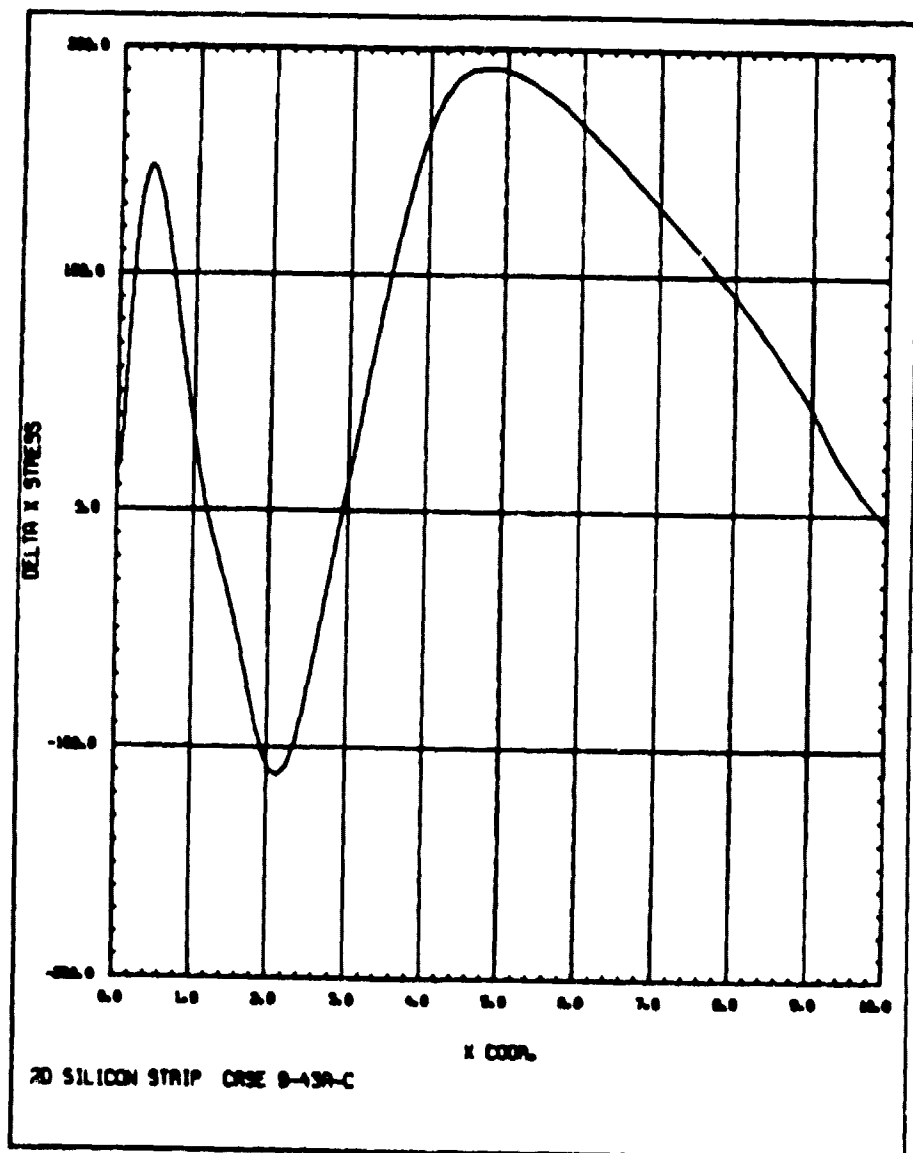Figure 1 -- Temperature profile results for J460 configuration.

Figure 2 -- Delta x-stress distribution for J460 configuration.

that the changes in the delta x-stress were negligible, the main effect being a slight shift of the stress curve corresponding to the shift in the position of the growth front. If, as suspected, the delta x-stress is a good measure of the driving force for ribbon buckling, then changes in the melt height should have little if any effect on the deformation of the web.

The changes in the y-stress components near the interface are more evident but still relatively small. The three cases are shown in Figure 3, where it can be seen that as the melt level falls (LIN increases), the y-stress on the ribbon centerline decreases slightly and the maximum value at about 0.5 cm also decreases. Although the visco-elastic deformation process is too complex for a detailed prediction of the resulting residual stress, intuitively it would appear that the lower melt levels would produce lower stresses. Inspection of the curves in Figure 3 shows that, while there is some difference between the three cases, the differences in fact are relatively minor, and it may be that the resulting stress differences will be too small to be clearly evident in the material measurements. In fact, the J460 material that has been evaluated all shows very low residual stress, and differences between material grown at high melts and that grown at low melts are small.

The major differences between the high melt (LIN = 0) and the lower melts (LIN = 0.1, 0.2) show up in the velocity effect. The web partial velocity, VV, changes from 1.52 cm/min (LIN = 0) to 1.18 cm/min at LIN = 0.2; a similar, although much smaller, decrease occurs in the melt contribution to the velocity. The net result is that changing the melt level (growth without replenishment) drastically affects the attainable velocities for web growth. On the other hand, the result means that when melt replenishment is available, the melt height can be used as an adjustable thermal parameter; growth could be initiated at a lower melt level where seeding seems to be easier, and then the melt level gradually increased to allow a relatively fast speed for steady-state growth.
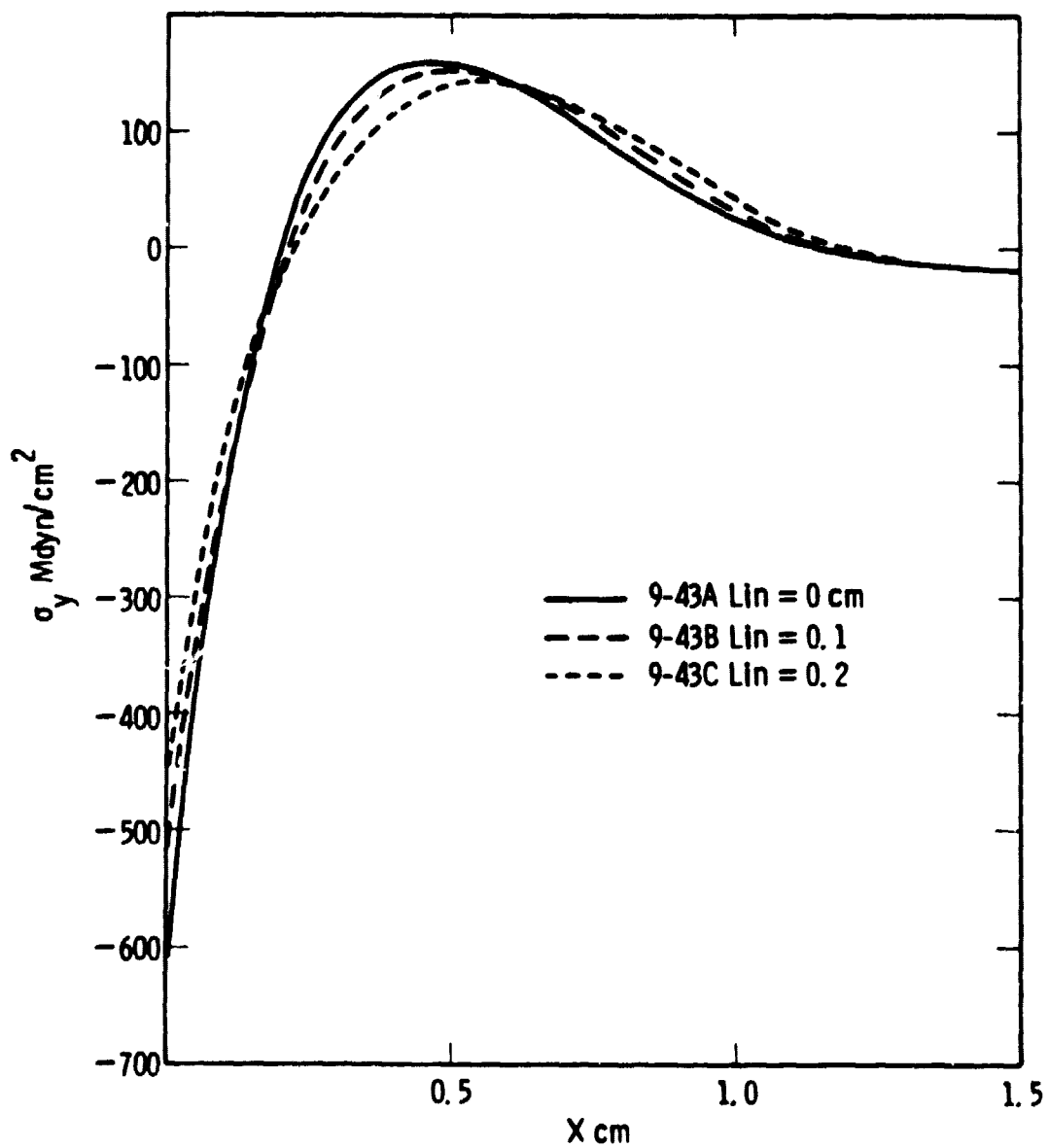
7

Curve 742148-A

Figure 3 -- Y-stress versus position -- J460 configuration.

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Current measurements of melt height will allow a more direct comparison of the measured growth performance with these calculated predictions. One factor, however, is missing: the meniscus height. This data should be recoverable from a study of decanted webs, and such a study is planned.

3.1.1 Low-Stress Designs

In addition to doing parametric studies on existing designs, some modeling work was done on the development of concepts for further stress reduction. Following indications that a higher shield stack reduced the buckling stress, a design with a 5 cm high stack was evaluated. The resulting $(\alpha T)''$ plot is shown in Figure 4 for one of the models that was run. The maximum in $(\alpha T)''$ is only 1.1×10^{-4} cm^{-2}, which is much smaller than values found for previous configurations. The reduction in $(\alpha T)''$ is reflected in the delta x-stress distribution as shown in Figure 5. The "far maximum" in the delta x-stress has been reduced to about 110 Mdyn/cm^2 and is in fact less than some of the stress maxima nearer the interface. Future design efforts will be directed toward further reduction in stress, but with emphasis on these "near" maxima in addition to the "far" maxima. When sufficiently good results have been achieved, then more complete analysis will be performed, including the buckling calculations, and an appropriate hardware design will be formulated.

3.2. Experimental Web Growth

3.2.1 Growth Experience

A width control version of the low-stress J460 configuration, designated the J460L, was designed and fabricated. Feed and laser holes for continuous melt replenishment were included in the lids and top shields. These parts were configured so as to prevent oxide accumulation during long duration runs, following the design parameters previously determined and tested empirically. The target steady-state
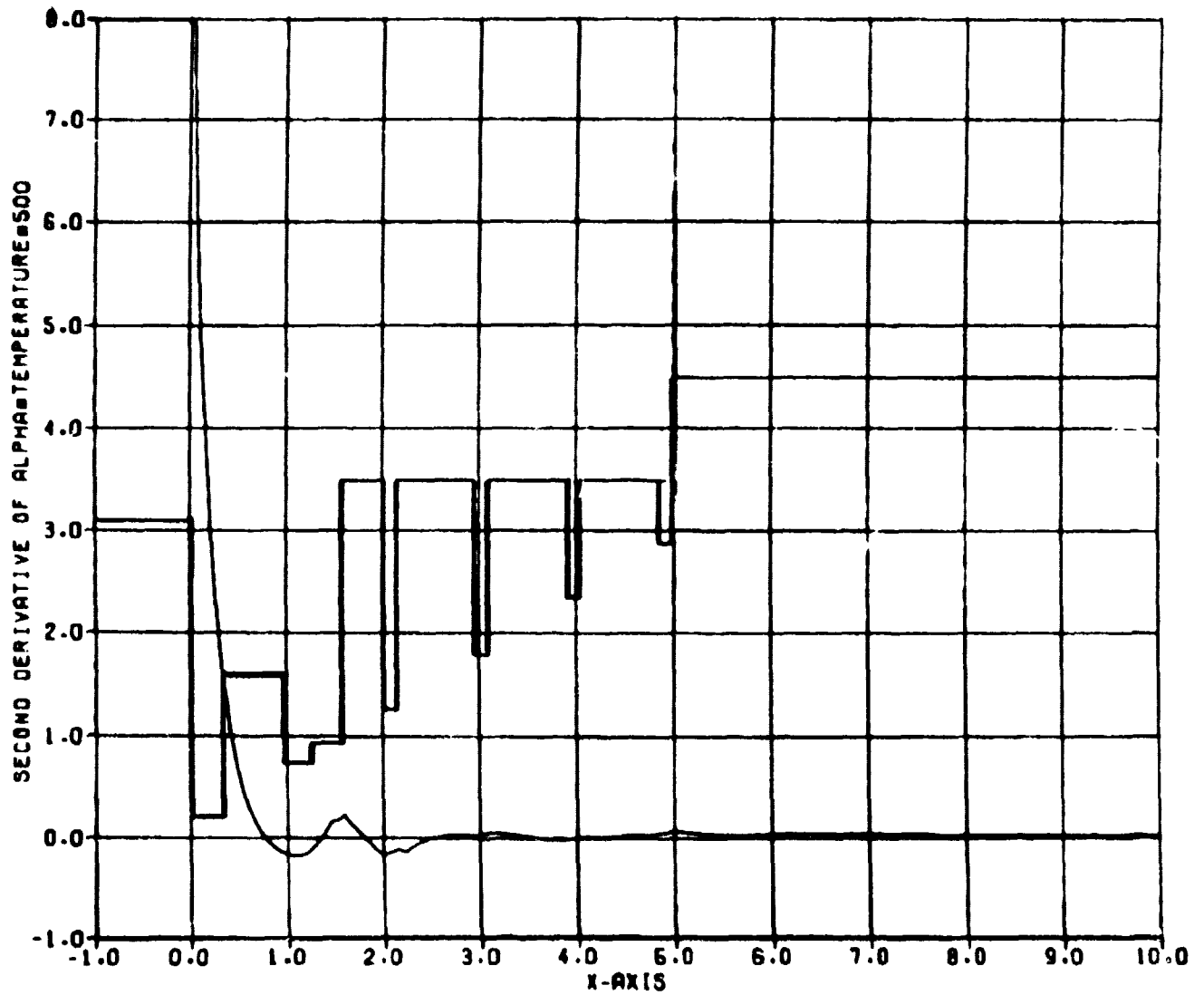
9-48

Figure 4 -- Temperature profile results for a 5 cm stack design.
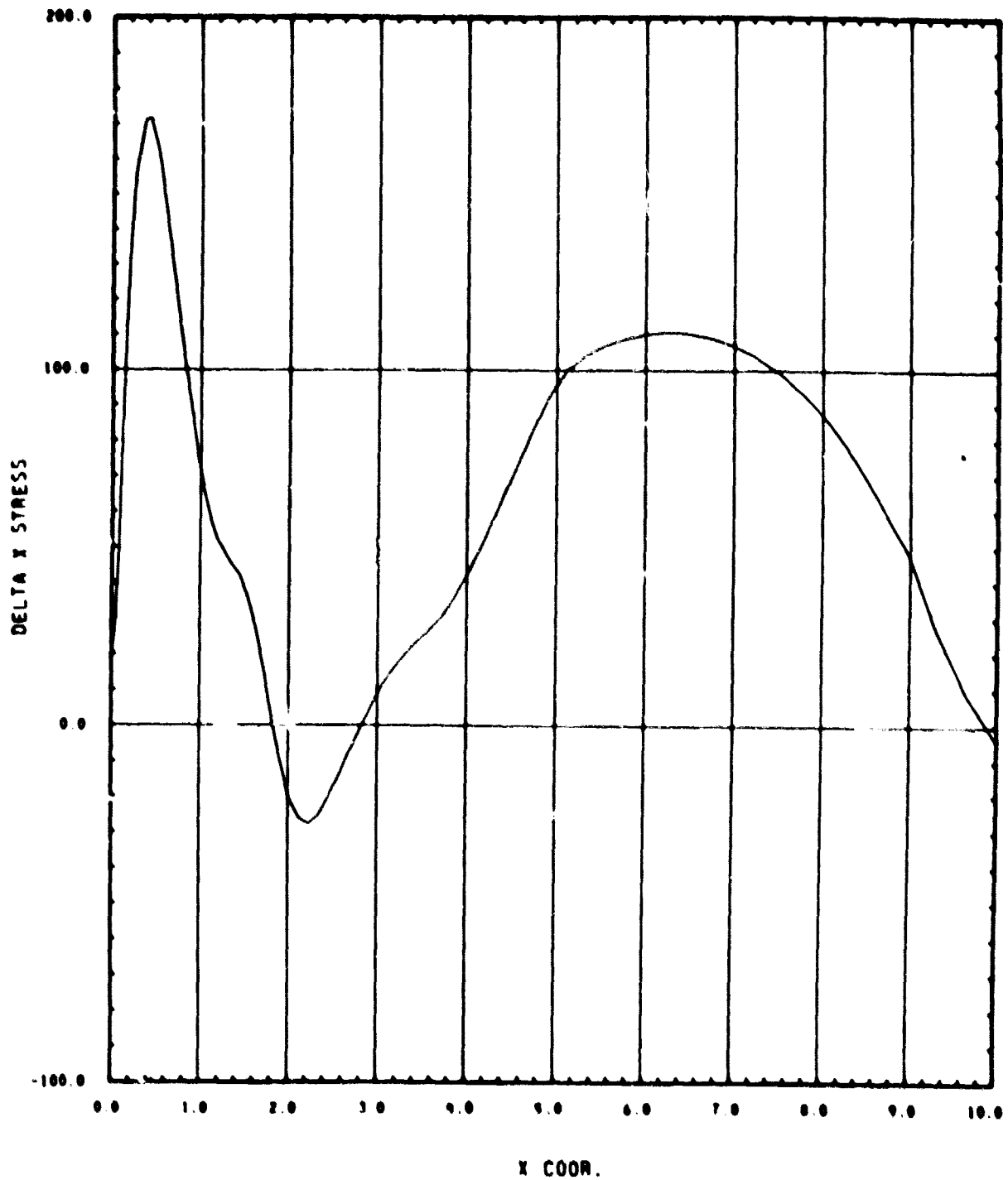
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2D SILICON STRIP   CASE 9-48C-C

Figure 5 -- Delta x-stress for 5 cm stack design.

web width for this design was 4 cm, well below the width at which thermal stress-generated buckling would occur in the baseline J460 configuration.

The first run with the J460L was made in the J-furnace with the first and fourth top shields instrumented to provide real temperature data. The growth results were quite encouraging. The first crystal was 5.1 meters long and reached a width of 4.1 cm, consistent with the design goal. The melt was replenished continuously during the last 2.5 hours of growth. During the second day of this run, two additional crystals were grown -- the first to lower the melt, the second with replenishment at a rate somewhat higher than the withdrawal rate -- in order to test growth behavior at different known melt levels. The thickness velocity characteristics and residual stress were also determined for different melt levels. Although there were some small differences, the general growth behavior of the J460L configuration was consistent with that of the basic J460 design.

Several runs were made with the J460L in the N-furnace with melt replenishment during part of the growth periods. Each run was carried over for a second day. Crystal widths to 4 cm were obtained with growth periods to 3.5 hours. However, growth behavior was not entirely reproducible during these runs, suggesting that shield and coil positions have not been fully optimized.

One run was made with a modified J460 in which the slot width in the lower lid was reduced from 6 mm to 4 mm. The purpose of this run was to verify the prediction of the model that narrowing the slot would enhance growth velocity by reducing the exposure of the web to the hot melt surface. The experimental results did indeed show a small increase in growth velocity and with minor coil adjustments good growth, although the physical dimension of the narrow slot required considerable care on the part of the operator during growth initiation.

3.2.2 System Measurements

Two types of system measurements were made during growth runs in the J-furnace: top shield temperatures and melt level. The purpose of these measurements was to provide data to quantitively relate system temperatures and melt position to observed growth characteristics, such as the thickness-velocity relationship.

Top shield temperatures were measured with type-K thermocouples cemented into small holes drilled partially through the shields close to the edge of the slots. Thermocouple outputs were fed into a data logger which prints out the shield temperatures as desired. Temperatures are recorded at "hold" and "grow." Temperatures were measured as a function of coil height and shield spacing. In most runs, temperature data were obtained for the lowest and highest top shield. This information was correlated with observed growth behavior and used as input to refine the temperature model calculations.

The device used for measuring melt level consists of a depth gauge micrometer with a quartz rod extention ground to a point at the tip. Knowing the distance from the top of the furnace chimney to the top of the susceptor, i.e., the bottom of the lid, one can readily determine the distance between the melt surface and the bottom of the lid to within 0.1 mm by measuring the distance from the top of the chimney to the melt surface and taking the difference between the two values.

4. CONCLUSIONS

Application of the models to test the effect of melt position on stress generation in the web showed that melt height should have little if any effect on the buckling stresses. Differences in the y-stress components near the interface are also small, although it appears that lower melt levels may produce lower stresses. Evaluation of web grown with the J460 configuration shows low residual stress at both high and low melt levels. Growth velocity, however, is sensitive to melt level so that growth at the higher melt levels is highly advantageous in terms of throughput.

Experimental testing of a width-limiting version of the low-stress J460 configuration gave results consistent with the design objectives, although the furnace parameters have not yet been optimized.

5. PLANS AND FUTURE WORK

New lower stress design concepts will be evaluated with the
models and the most promising fabricated for experimental testing.
Parametric sensitivities will be tested with the model in order to
access the factors which may be appropriate for dynamic trimming of the
growth system. Experimental work will continue with the J460L
configuration to optimize the parameters related to steady-state growth.

6. NEW TECHNOLOGY

No new technology is reportable for the period covered.

7. REFERENCES

1. C. S. Duncan et al., Silicon Web Process Development, Annual Report, April 1978 – April 1979, DOE/JPL 954654-79/2, p. 154.

2. C. S. Duncan et al., Advanced Dendritic Web Growth Development, Annual Report, October 1981 – October 1982, DOE/JPL 955843/83/8, p. 47.

8. ACKNOWLEDGEMENTS

9. PROGRAM COSTS

9.1 Updated Program Plan

    9.1.1 Milestone Chart

    9.1.2 Program Labor Summary

    9.1.3 Program Cost Summary

9.2 Man-Hours and Costs

Man-Hours:

Previous	31,810
This Quarter	1,129
Total	32,939

Costs:

Previous	$1,456,727
This Quarter	$61,284
Total	$1,518,011

Dwg. 4257813

FSA PROJECT
LARGE AREA SILICON SHEET
ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT
MILESTONE CHART - JPL CONTRACT 955843, MOD. 10

Task	1982 J J A S O N D	1983 J F M A M J J A S O N D	1984 J
1. Develop, Refine and Apply Computer Models for Expanding Basic Understanding of Silicon Ribbon Growth	██████		
a. Using Models, Develop New-Generation Web Growth Configurations	▲ (A) ▲ (O) ▲ (D)	△ (A) △ (J) △ (A) △ (D)	
2. Operate Experimental Growth Machines in Conjunction with Models to Support understanding of Silicon Web Growth	██████ ▲ (O)		
a. Evaluate New-Generation Configurations		△ (F) △ (M) △ (J) △ (O)	
b. Demonstrate 30 cm²/Minute Growth			
c. Demonstrate 35 cm²/Minute Growth		△ (J)	
3. Provide Web Samples to JPL	██████ As Directed By JPL		
4. Conduct Reviews			
5. Support Meetings	As Directed By JPL		
6. Provide Documentation Required by JPL	██████		J

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Program Labor Summary
JPL Contract 955843, Mod. 10
— — — Planned Hours
——— Actual Hours

ORIGINAL PAGE IS
OF POOR QUALITY

Direct Labor Hours (× 1000)

Program Cost Summary
JPL Contract 955843, Mod. 10
--- Planned Cost
—— Incurred Cost

Curve 740811-B

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Program Cost ($ × 1000)

1700   1650   1600   1550   1500   1450   1400

Contract Months

J J A S O N D J F M A M J J A S O N D J
1982   1983   1984

22